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MODERN SHEET-GLASS CUTTING TECHNOLOGIES

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The main types of sheet-glass cutting are examined. Mechanical roller cutting, being the most widely used cutting method at the present, is described in greatest detail. The effect of the roller geometry and load on the edge quality is explained. A general description of the hydro-abrasive and laser cutting technologies is also presented. The advantages and disadvantages of the existing technologies are indicated.

Key words: mechanical roller cutter, cutter parameters, hydro-abrasive cutting, laser cutting.

A high-quality defect-free edge is one of the main factors preserving the strength of glass during processing and use.

It is well-known that defects form in large or small numbers on a glass edge during cutting and these defects increase the risk of the following:

– fracture of the glass during heat-treatment (hardening, hardening by heat-treatment, or mollification); for this reason edging is always performed before this operation;

– spontaneous fracture of the glass as a result of thermal shock;

– fracture of the glass under loads occurring during service — loads due to wind and snow, self-weight.

The need to assure acceptable edge quality with minimum technological inputs makes it necessary to develop new cutting technologies and improve existing ones. This article reviews the main methods used to cut sheet glass and affect the technological parameters of the quality of a cut.

MECHANICAL CUTTING

The overwhelming majority of processers currently use mechanical roller cutting for sheet glass. The rollers have a wedge-shaped obtuse-angle section and are manufactured from hard alloys, primarily alloys based on tungsten carbide (Fig. 1).

The cutting proceeds in two stages: first a scratch (groove) is made and then a bending force is applied across the cut line (a break is made).

A groove remains after the roller has passed along the surface of the glass. A network of intersecting cracks forms in the surface layer subject to a shear load; the trajectory of the network coincides with the action of the shear stress.

In addition, partially plastic deformation of more distant layers occurs and gives rise to stresses which cause the cracks to grow. Three types of cracks can be identified: surface, lateral, and central normal (Fig. 2). To obtain a correct cut the break must pass along the central crack (perpendicular to the surface of the glass) [1].

The roller geometry has a considerable effect on the formation and growth of cracks. The minimum load P_c required for a crack to form is directly proportional to the sharpening angle and its radius and is expressed by the relation [2]

$$P_c = \frac{K_{1c} \tan(\psi)^{5/2} \sqrt{R}}{4\gamma E^3 k}. \qquad (1)$$

The coefficient k in this expression depends on the properties of the contact materials and is determined by

$$k = \frac{1-\nu_1^2}{E_1} + \frac{1-\nu^2}{E}, \qquad (2)$$

where K_{1c} is the coefficient of the critical stress concentration; ψ is half the sharpening angle of the roller; R is the ra-

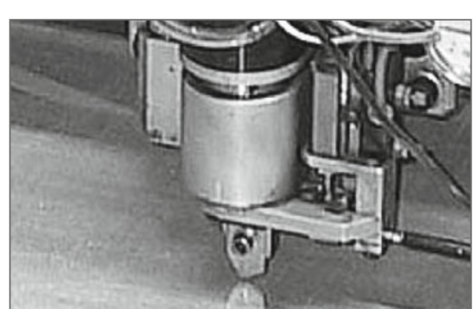

Fig. 1. Cutting head.

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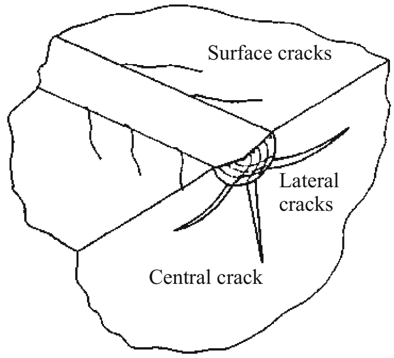

Fig. 2. Crack formation scheme produced in glass by a cutting roller.

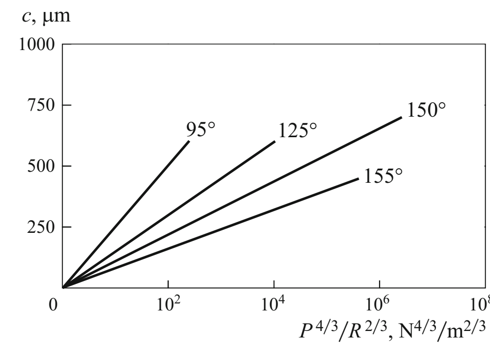

Fig. 3. Crack depth c versus the applied load and the roller radius $P^{3/4}/R^{2/3}$. The sharpening angles of the rollers are presented on the curves.

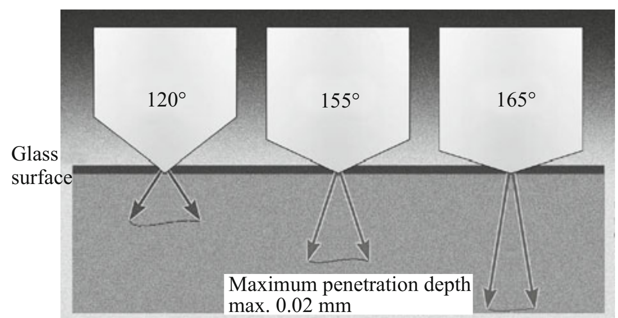

Fig. 4. Boundaries of the region of the stresses developed for rollers with different sharpening angles; the maximum penetration depth of a roller is 0.02 mm.

dius of the roller; γ is a constant that depends on the stress ratio required to form cracks to the stress left by the roller; E_1 and E are Young's modulus of the glass and roller, respectively; and, ν_1 and ν is the Poisson ratio of the glass and roller, respectively.

After a crack is formed, it starts to grow to equilibrium dimensions as a result of the relaxation of the stresses arising in the surface layers as a result of the wedging action of the roller and the residual stresses in the glass.

According to [2] the intensity of the stresses increases with the load and decreases with the sharpening angle of the roller; the depth of the cracks is proportional to the intensity of the stresses (Fig. 3):

$$K_c = \frac{P\sqrt{1-\nu_1^2}}{L\tan(\psi)\sqrt{c\pi}}, \tag{3}$$

where K_c stress intensity coefficient, L is the length of the contact, and c is the depth of the crack.

The forces exerted by a roller on the glass are directed perpendicular to the edges of the glass and act in shear in the adjoining layers [3]. The deformed layers pull the layers directly above them, creating tensile stresses in them. The sharper the roller, the farther away the forces are felt from the normal to the glass surface and therefore the wider but shallower the region of the stresses which are created (Fig. 4).

The sharpening angle of a roller is set on the basis of the thickness of the glass. A large force is required to break thick glass, and this has a negative effect on the edge quality. To decrease the breaking force tensile stresses must be introduced along the line of the cut, and for this the force with which the roller is pressed against the glass must be increased. If acute-angle rollers are used, good conditions are created for undesirable lateral cracks to grow. For this reason obtuse rollers, whose action is directed primarily downwards, are used for thick glass.

However, obtuse rollers are undesirable for thin glass, since according to the relation (1) the pressure must be increased. It is easy to break through thin glass. On the other hand there is no need to create a deep region of stresses; after all, the breaking force is small in any case. For this reason acute-angle rollers are used.

Special liquids which make it possible to obtain a high-quality cut are used in roller cutting. These liquids have the following functions:

– lubricating the roller (increases roller service life);

– creation of a hydraulic cushion (gives a more uniform force distribution);

– decreases the surface area of the glass (Rebinder effect) as a result of SAS in the liquid, which improves cutting;

– creates a wedging effect, preventing "healing" of the cracks after passage of the roller;

– decreases the contamination of the table by glass chips, which adhere to the liquid;

Mechanical roller cutting has the following advantages:

– equipment is inexpensive;
– operation is simple;
– operating costs are low;
– cutting speed is high (reaches 120 m/min);
– sheet glass with large dimensions can be cut.

But mechanical cutting has the following disadvantages:

– relative poor quality of the cut;

– degradation of cutting quality because of the drawbacks of the glass (nonplanarity, high residual stresses, and soon);
– need to use a liquid for cutting;
– need to edge the glass when subsequent heat-treatment of the glass is needed.

HYDRO-ABRASIVE CUTTING

A water jet was first used to solve technical problems in the mining industry, specifically, gold mining in the 1970s. Subsequently it developed as a result of applications for washing away rocks and washing strong contaminants from various surfaces before cutting different materials with a water jet.

In the 1980s it became possible mix into a water jet, propelled by a powerful water pump, particles of solid materials. This made it possible to process practically all materials by means of hydro-abrasive cutting. When cutting with pure water the static pressure from a compact jet, just as with the erosion action of a ordinary water drop, washes out material; but, when solid particles are added to the jet microcutting of the material occurs. This permits cutting materials which cannot be cut solely by means of water and makes the cutting process considerably more productive. Sharp-tipped granules of comminuted minerals, such as garnet sand or olivine, with grain size ranging from 0.1 to 0.3 mm are used as abrasives. Depending on the applications, the amount of the abrasive use ranges from 100 to 500 g/min.

The pressure of the jet during hydro-abrasive cutting reaches 400 MPa. The diameter of a jet is 0.6 – 1.2 mm.

The cutting speed affects the edge squareness and quality. The slower the cutting, the more even, square, and smooth the edge will be.

Hydro-abrasive cutting cuts glass very well. The edges have a mat and slightly rough surface and can be ground and polished using less force than the edges obtained after cutting and breaking.

Hydro-abrasive cutting is used in practically all areas of industry where solid, multilayered materials are processed as well as to manufacture articles with a complex shape. This technology is ideal in cases where thermal or mechanical processing of articles is impossible, for example, the manufacture of the structural components in building aircraft and in the space industry.

In the glass industry, hydro-abrasive cutting is practically indispensable for cutting bullet-proof glass, multilayer triplex, and fire-resistant glass and it has essentially replaced completely the cutting of glass by means of a cutting tool.

Hydro-abrasive cutting possesses the following advantages:
– good edge quality;
– grinding not required;
– negligible effect on the material:
  thermal (no thermal stresses on the edges);
  mechanical (negligible pressure on the glass — no cracking);
  chemical (no chemical interaction between the glass and abrasive);
– possibility of cutting very thick and multilayered glasses.

The main disadvantages are:
– high cost of equipment;
– high operating costs;
– low cutting speed (0.5 – 1.5 m/min depending on the edge quality and glass thickness);
– need for purifying water;
– useless, up to harmful, residual energy of the jet (must be captured);
– cost of sludge removal and salvaging [4].

LASER CUTTING

Laser cutting was first used in metal processing for high-precision cutting of sheet steel up to 20 mm thick. This process occurs as a result of evaporation of the metal in the cutting zone along the entire thickness.

Laser technologies came into use for glass cutting comparatively recently. Thus, they already have found application for cutting hollow glass dishware, glass for liquid-crystal monitors, and solar batteries. Laser cutting is now being adopted for cutting sheet glass.

LASER CUTTING BY THERMAL EVAPORATION

This technology, which is close in principle to the metal cutting technology used for glass is called cutting by thermal evaporation and has been tested in the manufacture of hollow glass dishware (cutting off caps) [5]. The cutting was done with a continuous-wave CO_2 laser. It was possible to obtain a good-quality cut with a rounded edge. But the process itself was very energy intensive and slow. For a 200 W laser the cutting speed for 3 mm thick glass was 6 mm/min.

Another drawback is the appearance of residual stresses in the glass because of the action of heat and, in consequence, high proneness of the glass to cracking. This requires subsequent annealing.

As it turned out subsequently, the glass need not be evaporated all the way through. The low thermal conductivity and heat-tolerance of glass make it possible to cut glass by thermal splitting. The energy consumption is much lower in this case.

LASER CUTTING BY THERMAL SPLITTING

The principle of laser cutting by thermal splitting consists in creating thermal stresses that exceed the maximum strength of the glass and result in splitting of the glass.

First the glass is heated by laser radiation along the proposed line of splitting. The low thermal conductivity of the

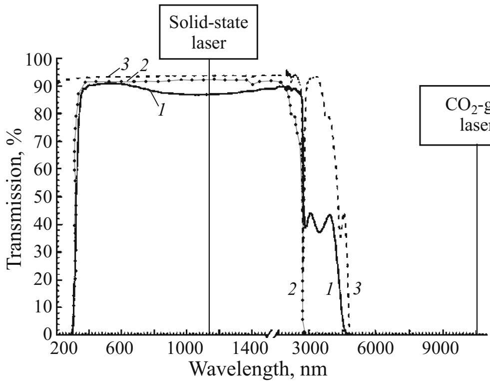

Fig. 5. Light transmission of glass: *1*) float glass; *2*) borosilicate glass; *3*) fused silicon.

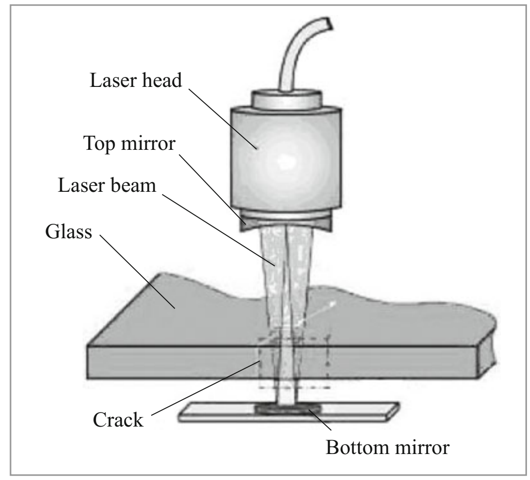

Fig. 6. Scheme of the technological process of multiple absorption of laser radiation (MALR).

glass makes is possible to obtain the required profile of the temperatures and stresses on a local section.

Next the glass is cooled. As a result, tensile stresses leading to the appearance of cracks arise on the pre-heated section. The conditions for crack growth can be described by means of the energy approach:

$$-\,\mathrm{d}\Phi \geq C\mathrm{d}A, \tag{4}$$

where $\mathrm{d}\Phi$ is the change in the elastic deformation energy and is proportional to the stresses; $\mathrm{d}A$ is the change in the surface area of a crack; and, C is the specific surface energy.

It is obvious that crack propagation requires that the work performed as a result of the removal of stress be not less than the energy required for a new surface to form. The best surface quality (minimum relief) obtains when the elastic energy released during crack growth is slightly greater than or equal to the formation energy of new surfaces.

When laser heating is used, the parameters of the radiation (power, spot size and shape) can be determined quite accurately, thereby ensuring the required stresses for obtaining a perpendicular, perfectly even, edge.

There exist two types of thermal splitting depending on the wavelength of the laser radiation. Figure 5 displays the radiation wavelength of two types of lasers and spectra of a number of materials.

GAS LASERS (CO_2 LASERS)

The CO_2 laser wavelength is approximately 10.6 µm. Such radiation does no penetrate into the interior volume of glass, and all energy goes into heating the surface. During the subsequent cooling tensile stresses appear in the surface layer and result in the formation of cracks.

In the standard applications of this technology a crack of depth equal to 20% of the thickness of the glass is obtained, after which mechanical breaking is performed. But the heating can be continued and instantaneous cleavage of the glass through the entire thickness can be achieved [7].

For a long time this type of cutting remained very slow. Since the surface of glass is capable of absorbing a definite amount of energy, when overheating occurs there appears a nonstationary field of high stresses which relax via the formation of many chaotic cracks. Ultimately, it is impossible to obtain a single required crack for a correct break.

The authors of [7] found a solution of this problem. It was found that an arbitrarily large amount of energy can be supplied to a glass surface but only after a definite amount of time required for the energy to pass into the interior layers. This time is equal to 3 msec. Discrete heating made it possible to increase the average power of the radiation and cutting speed substantially.

A large advantage of this technology is insensitivity to residual stresses in the glass. The authors of [7] also assert that this method can be used to cut hardened glass.

In Russia, the Institute of Technical Glass is developing the laser cutting technology. Cutting with a CO_2 laser has been successfully adopted in the Saratov Glass Works for transverse cutting of a float-ribbon [8].

SOLID-STATE LASERS

The radiation wavelength varies from 1036 to 1064 nm. About 90% of the radiation passes through the glass and only 10% is absorbed in its volume. This is inadequate for the required heating to occur, so that multiple absorption of laser radiation (MALR) technology is used. Figure 6 shows the scheme of this process [9]. The laser beam passes several times through the glass, reflecting from the top and bottom mirrors.

The glass is uniformly heated over the entire thickness. As the glass cools, tensile stresses appear and cause the glass to break along the entire thickness.

Research has revealed several drawbacks to this technology [7]. The objective of this research was to create a sec-

tion of laser cutting on a production line for sheet glass. It was found that the cutting quality is strongly affected by a change of the temperature or stresses in the glass (whether residual, thermal, or mechanical stresses). Even securing the glass mechanically had a negative effect on the cutting process.

On the whole, laser cutting has the following advantages [7, 8, 9, 10, 11]:

– ideal quality of the cut (even, perpendicular to the edge with no chipping or skin cracks);

– cutting without the use of oil;

– cutting of thick and multilayer glasses;

– possibility of detailed regulation of the radiation parameters;

– no need for grinding and polishing edges;

– no mechanical contact with glass or part wear.

The disadvantages are:

– impossibility of processing glass reflecting infrared radiation (low-emission) from the low-emission coating side [7];

– high cost of equipment;

– relatively low speed (5 – 10 m/min);

– lack of, to this day, tables for working with a PLF format (3.21 × 6 m).

CONCLUSIONS

For a long time mechanical roller cutting was the only technology available for industrial processors of glass. In addition, although such a technology combines low costs and productivity it is impossible to obtain a cut of ideal quality. Laser cutting can solve this problem. Even though the equipment for laser cutting has been on the market for a long time, this technology is not widely used. The main impediments are the high cost of the equipment and the lack of tables for working with large pieces of float-glass.

Another method is hydro-abrasive cutting. By virtue of its specific nature it is used only to cut multilayer glass or to obtain glass articles with a complicated contour.

In summary, considering the particulars of each of the three existing methods of cutting, it can be asserted that mechanical roller cutting of sheet glass will be the dominant technology in the foreseeable future.

For this reason, improving it remains an important problem today.

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